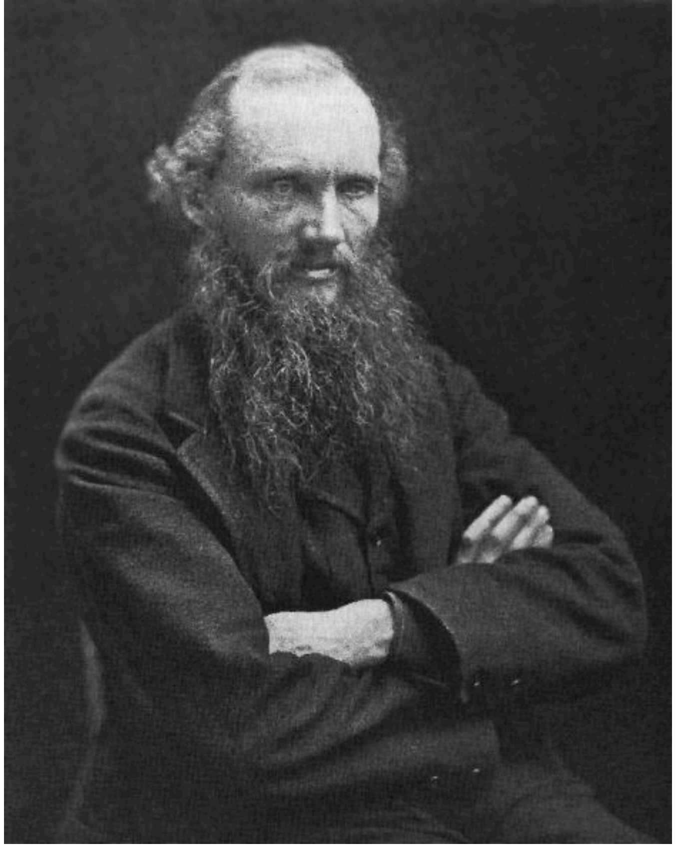


There is nothing new to be discovered in physics now. All that remains is more and more precise measurement.

Lord Kelvin, British Association for the Advancement of Science, 1900

Photons and Di-leptons:

Mickey Chiu, Tom Hemmick, Vlad Khachatryan Andrei Leonidov, Jin Feng Liao, Larry McLerran

Are they direct probes of the Glasma state?
Of Bose Condensation?

Outline:

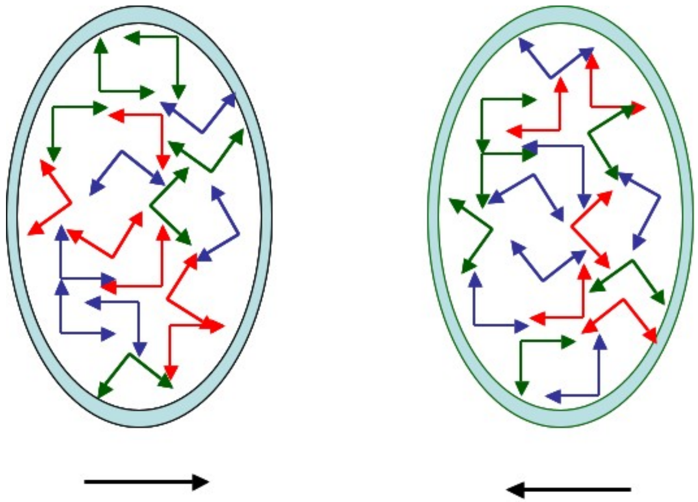
How does thermalization appear in the Glasma and is there possible formation of a Bose Condensate?

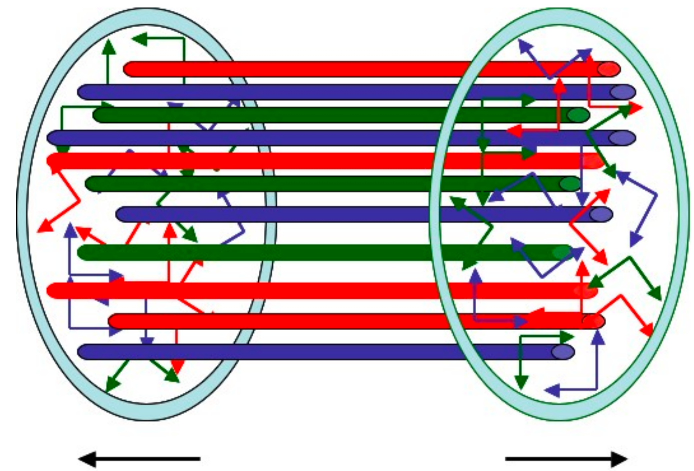
What are the implications for photon and di-lepton emission?

Problems of interpreting Phenix data on photons and di-leptons as arising from thermally equilibrated system.
Fits to the Phenix data?
What data do we need?

Collisions of two sheets of colored glass

Sheets get dusted with color electric and color magnetic fields





Long range color fields form in very short time

Maximal local density of topological charge: Large local fluctuations in CP violating

$$\vec{E} \cdot \vec{B}$$

Glasma: Matter making the transition for Color Glass Condensate to Quark Gluon Plasma

The initial conditions for a Glasma evolve classically and the classical fields radiate into gluons
Longitudinal momentum is red shifted to zero by longitudinal expansion

But the classical equations are chaotic:
Small deviations grow exponentially in time

Chaos and Turbulence:

CGC field is rapidity independent => occupies restricted range of phase space
Wiggling strings have much bigger classical phase space
A small perturbation that has longitudinal noise grows exponentially

$$A_{classical} \sim 1/g$$

$$A_{quantum} \sim 1$$

After a time

$$t \sim \frac{ln^p(1/g)}{Q_{sat}}$$

System becomes isotropic,

But it has not thermalized!
Entropy is being produced

Thermalization naively occurs when scattering times are small compared to expansion times. Scattering is characterized by a small interaction strength.

How can the system possibly thermalize, or even strongly interact with itself?

Initial distribution:

$$\frac{dN}{d^3x d^3p} \sim \frac{Q_{sat}}{\alpha_s E} \; F(E/Q_{sat})$$

A thermal distribution would be:

$$\frac{dN}{d^3x d^3p} \sim \frac{1}{e^{E/T} - 1} \sim T/E$$

Only the low momentum parts of the Bose-Einstein distribution remain

$$E \sim Q_{sat}$$

$$\text{“}T \sim Q_{sat}/\alpha_s\text{”}$$

As dynamics migrates to UV, how do we maintain isotropy driven by infrared modes with a scale of the saturation momentum?

Phase space is initially over-occupied

$$f_{thermal} = \frac{1}{e^{(E-\mu)/T} - 1}$$

Chemical potential is at maximum the particle mass

$$\rho_{max} \sim T^3 \qquad \epsilon_{max} \sim T^4$$

$$\rho_{max}/\epsilon_{max}^{3/4} \leq C$$

But for isotropic Glasma distribution

$$\rho/\epsilon^{3/4} \sim 1/\alpha_S^{1/4}$$

Where do the particle gluons go?

If inelastic collisions were unimportant, then as the system thermalized, the ratio of the energy density and number density are conserved

$$f_{thermal} = \rho_{cond}\delta^3(p) + \frac{1}{e^{(E-m)/T} - 1}$$

One would form a Bose-Einstein Condensate

Over-occupied phase space => Field coherence in
Interactions can be much stronger than

$$g^2$$

$$N_{coh}g^2$$

Might this be at the heart of the large amount of jet quenching, and strong flow patterns seen at RHIC?

Problem we tried to solve:

Blaizot, Gelis, Jin-Feng Liao, LM, Venugopalan

How does the system evolve from an early time over-occupied distribution to a thermalized distribution

We argue that the system stays strongly interacting with itself during this time due to coherence

Basic Physics:

$$f = \frac{\Lambda_s}{\alpha_s E} f(E/\Lambda)$$

Two scales: Coherence scale and UV cutoff

$$t_{scat} \sim \Lambda/\Lambda_s^2$$

Time dilation of basic time scale: $1/\Lambda_s$

Far from equilibrium, dimensional reasoning $t_{scat} \sim t$

Always strongly interacting: Coupling constant has disappeared

Energy of system is controlled in hard modes, not condensate
Expanding system has a momentum anisotropy

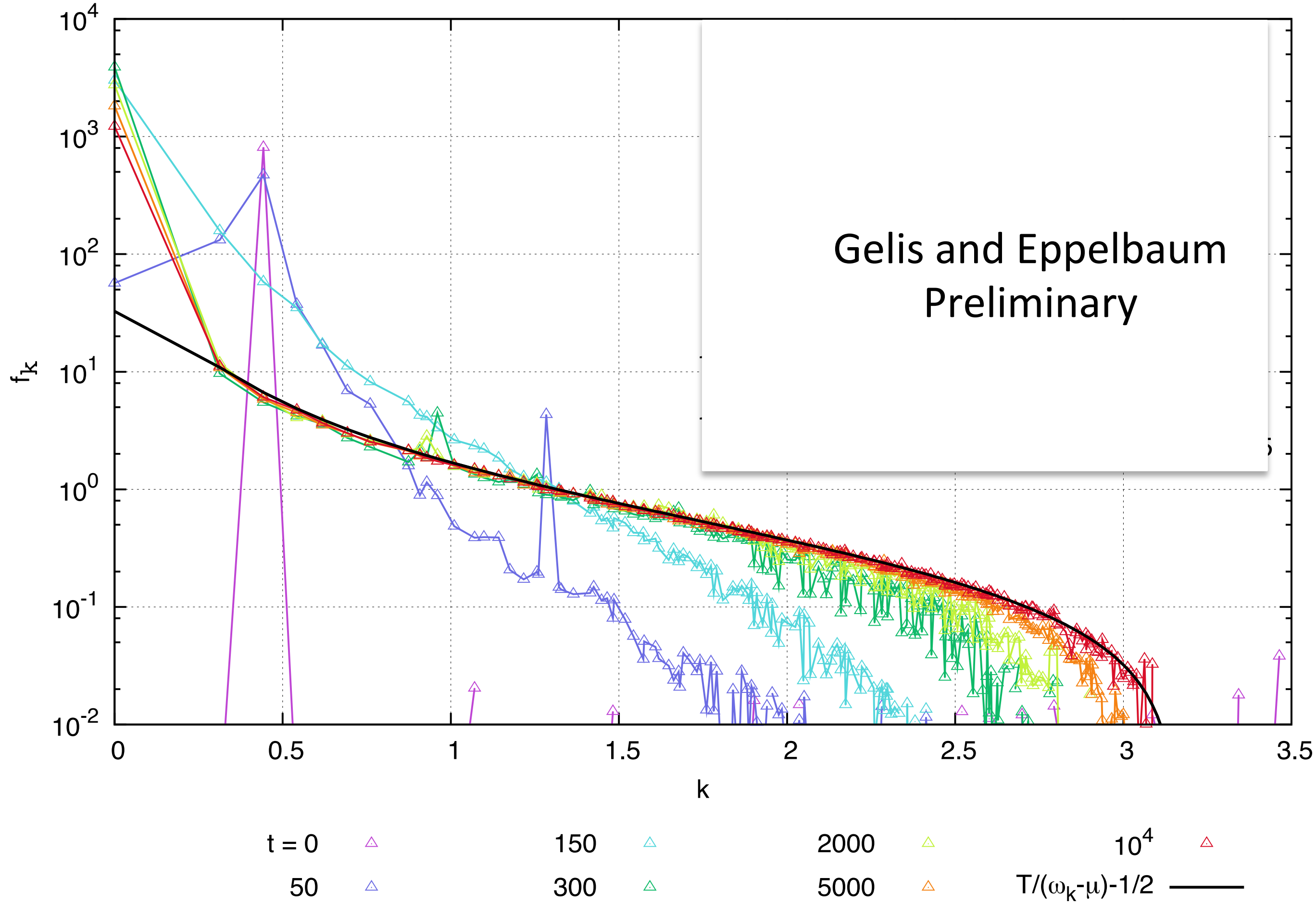
$$\partial_t f - \frac{p_z}{t}\partial_{p_z} f = \left.\frac{df}{dt}\right|_{p_z t} = C[f] \qquad \partial_t \epsilon + \frac{\epsilon + P_L}{t} = 0$$

$$P_L = \delta \epsilon \qquad 0 < \delta < 1/3$$

$$\epsilon_g(t) \sim \epsilon(t_0)\left(\frac{t_0}{t}\right)^{1+\delta} \qquad \Lambda_s \sim Q_s\left(\frac{t_0}{t}\right)^{(4+\delta)/7}, \qquad \Lambda \sim Q_s\left(\frac{t_0}{t}\right)^{(1+2\delta)/7}$$

$$\left(\frac{t_{th}}{t_0}\right) \sim \left(\frac{1}{\alpha_s}\right)^{\frac{7}{3-\delta}} \qquad < p_x^2 > / < p_T^2 > \sim constant$$

Simulations by Gelis and Eppelbaum seem to confirm this scenario in scalar field theory in non-expanding box



Rapid Reaction Task Force at Heidelberg sponsored by EMMI Dec 12-14

Features of photon and di-lepton emission:

Photons:

Excess with strong dependence on number of participants at 1-3 GeV

$$\frac{dN}{dyd^2p_T} \sim N_{part}^2$$

Photons flow, marginalizing thermal interpretation

Dileptons:

Excess in mass range ~ .5 -1 GeV

Excess comes from low transverse momentum range

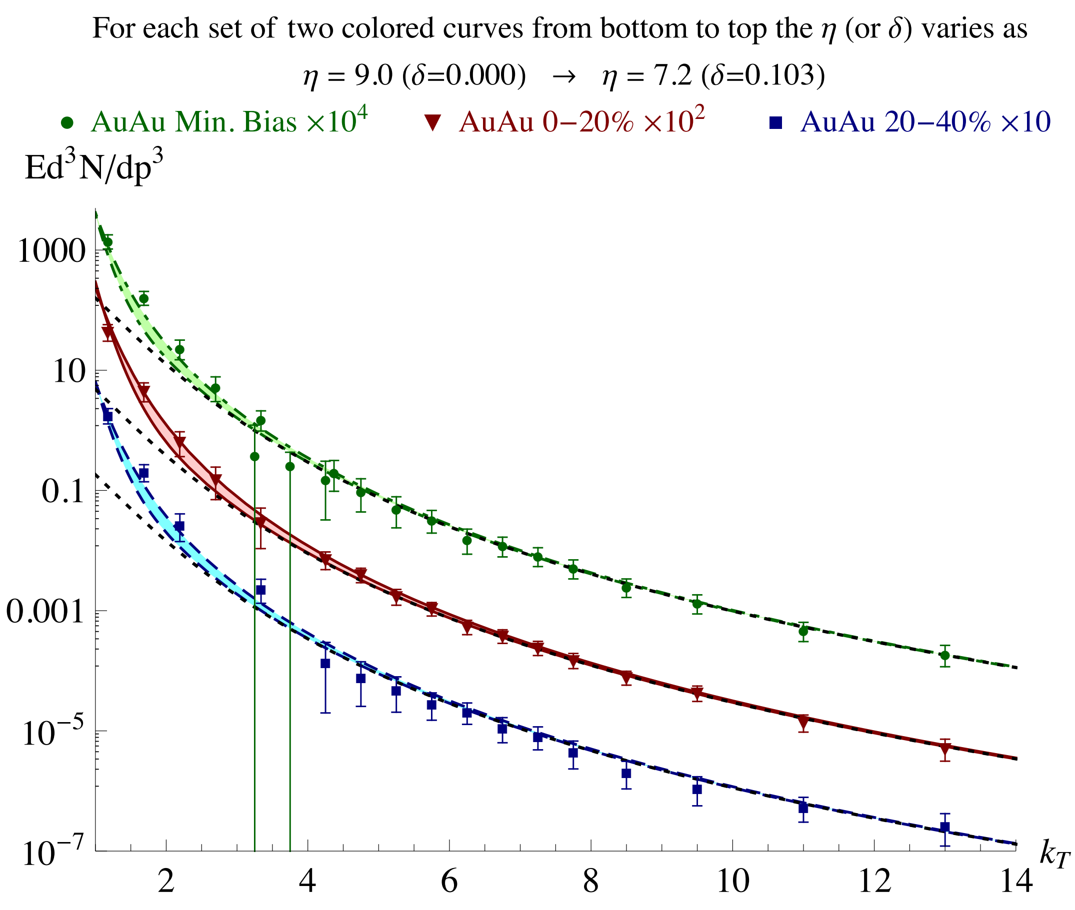
$$< p_T > \quad << \quad < M >$$

Inconsistent with hard production or thermal production

Photon production from the Glasma

Folding the photon production rate over the expansion of the Glasma:

$$\frac{dN}{dyd^2k_T} = \alpha R_0^2 N_{part}^{2/3} \left(\frac{Q_{sat}}{k_T}\right)^{\eta} \qquad \eta = (9-3\delta)/(1+2\delta)$$



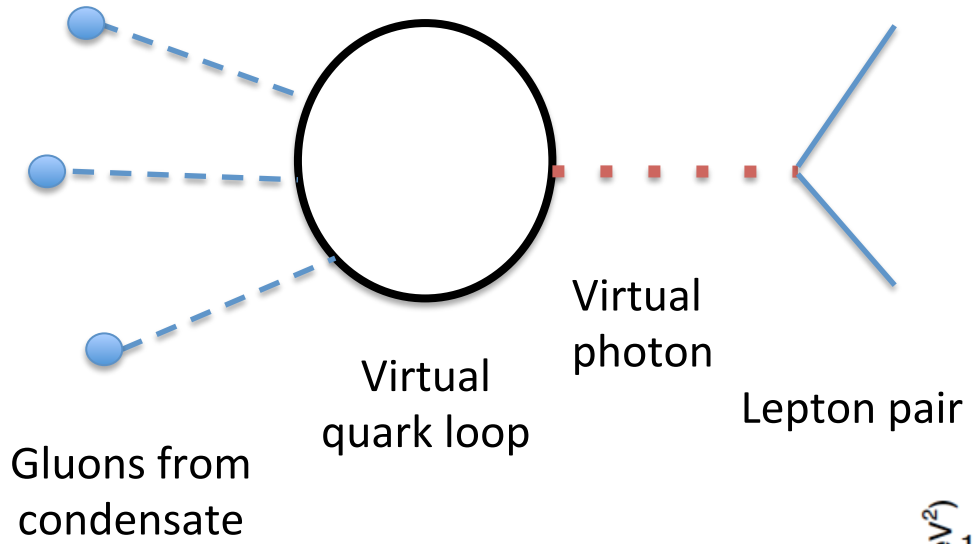
Delta: 1/3 for asymmetric expansion, 0 for maximally asymmetric

$$0 \le \delta \le .1$$

Good fit for

$$1\ GeV \le k_T \le 3\ GeV$$

Centrality dependence well described using Khareev Nardi result for saturation momentum



In region of di-lepton enhancement, effective temperature of 100 MeV

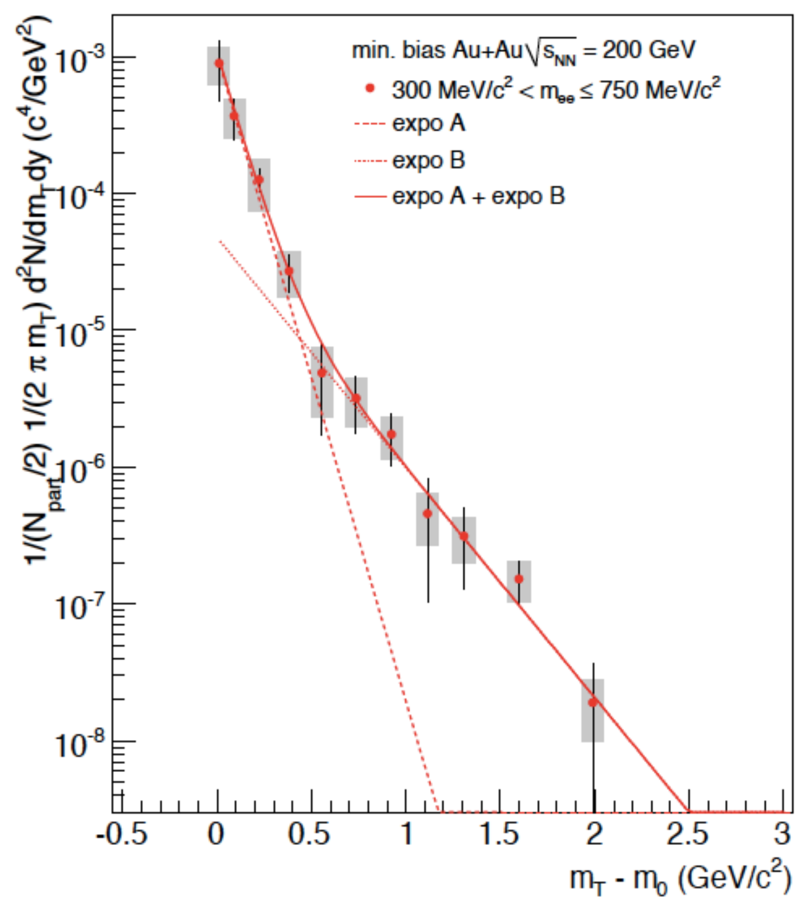
Inconsistent with thermal emission or hard particle scattering

Condensate gluon annihilation is same order in g as thermal quark-antiquark annihilation.

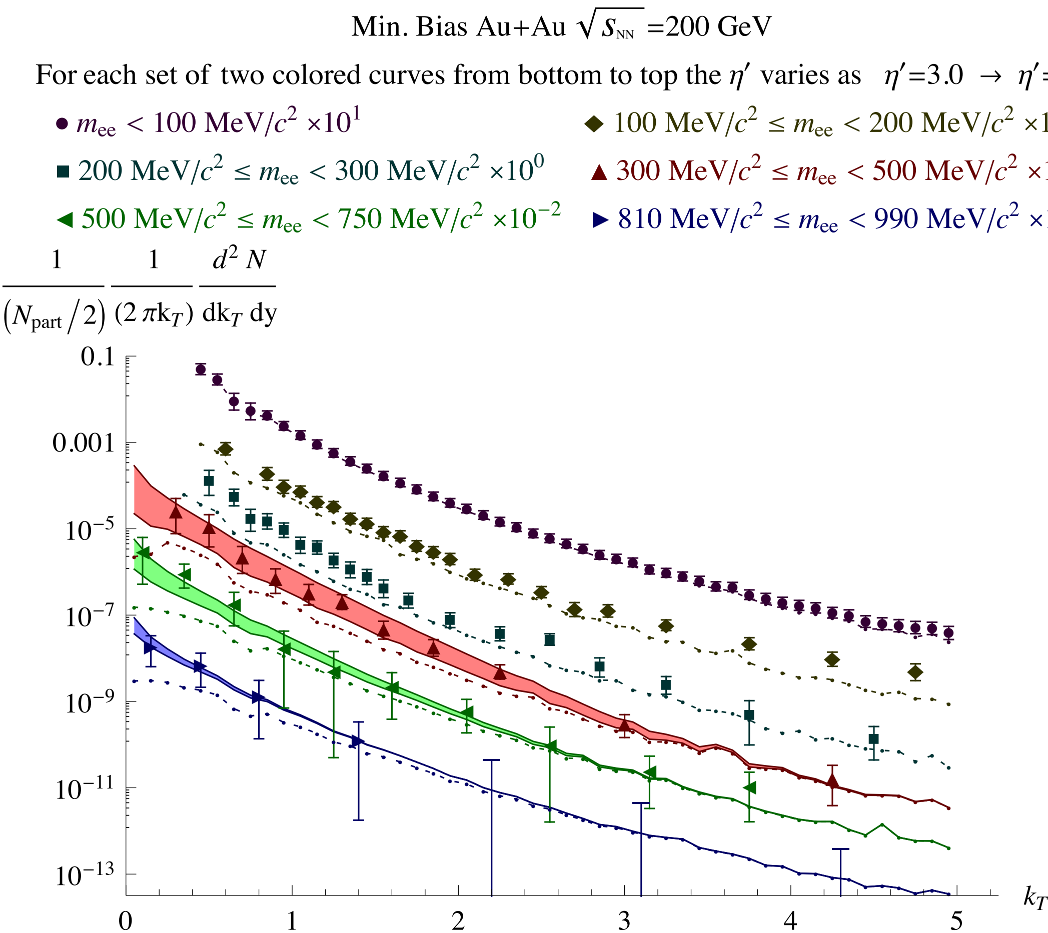
$$g \times 1/g \sim 1$$

Is somewhat softer and will dominate in lower mass and transverse momentum regions

Condensate gluons carry energy of order Debye mass, but zero transverse momentum



Fit dilepton mass spectrum for transverse momentum less than 500 MeV to power law in mass:



For three gluon emission

$$\frac{dN}{dydM^2} \sim \alpha^2 R_o'^2 N_{part}^{2/3} \left(\frac{Q_{sat}}{M}\right)^{\eta'}$$

$$\eta' = \frac{9(3-\delta)}{(5+3\delta)}$$

$$\eta' \sim 3 - 5$$

Upper end consistent with photon data; need better computation and better data

Predict $$dN/dydM^2 \sim N_{part}^{3/2}$$

Summary:

Photon and di-lepton data seem consistent with Glasma and Bose condensate hypothesis

Need simulation for photon v2

Need more and better data for:

Centrality dependence of di-leptons
Mass dependence for fixed transverse momentum and vice versa
How much of the enhancement really comes from very small transverse momentum

Potential for an exciting experimental discovery